REPORT OF PANEL ON TESTING IN ICE

1. GENERAL

The ice panel was created at the 14th ITTC, Ottawa, 1975. The Executive Committee realized that the discovery of minerals in the Arctic has led to the development of a number of refrigerated towing tanks. The interest in refrigerated towing tanks is continuing; currently two or three new facilities are well into the planning stage.

1.1 Composition of the Present Panel

Panel Members:	J. Alekseyev
	G. Frankenstein (Chairman)
	E. Makinen
	J. Schwarz
Others:	A. Keinonen
	S. Mathews (Executive Committee Rep.)
	G. Vance

1.2 Meetings of the Panel

The panel met on five occasions. The first meeting, held at Wartsila, Helsinki, Finland, 26, 27 Oct. 1976, was followed by sessions at HSVA, Hamburg, Germany, 19 and 20 May 1977; then at Leningrad, USSR, 12, 13 Oct. 1977; and at CRREL, Hanover, New Hampshire, USA, on 27, 28 Feb. 1978. The final meeting was held at Wartsila, 18, 19 April 1978.

1.3 Work of the Panel - General

The panel decided that the first order of business was to define an objective, which is "to develop a standard measurement system for ships and floating platforms in ice in laboratory and field conditions."

1.4 Areas of Consideration

The panel has prepared an outline of items that should ultimately be addressed to meet the basic objective stated in section 1.3.

1.4.1 Laboratory Tests

- A. Model material
  - a. similarity
  - b. preparation
  - c. properties
- B. Modeling environmental conditions
  - a. level ice
  - b. ridged ice
  - c. ice under pressure
  - d. broken channel ice
  - e. floe conditions
- C. Testing procedures
  - a. towing
  - b. self-propelled
  - c. maneuvering

D. Analysis
  a. presentation
  b. format
    - recommended standardized resistance equation
    - units and symbols
  c. method and non-dimensional parameters

1.4.2 Full Scale Tests

A. Ice
  a. properties
  b. conditions

B. Testing procedures
  a. continuous mode
  b. non-continuous mode
  c. maneuvering

C. Ship performance measurements
  a. trial
  b. voyage

D. Analysis
  a. presentation
  b. format
    - recommended standardized resistance equation
    - units and symbols
  c. method and non-dimensional parameters

1.4.3 Model-Full Scale Correlation

1.5 Near Term Considerations

The panel recognized that some items that may or may not appear in section 1.4 could be addressed immediately. These items are discussed briefly in this section.

1.5.1 Bibliography

Develop a bibliography on ice testing that will be made available at the conference.

1.5.2 Units of Measure

Recommend that S.I. units be used as the standard units of measure for all testing.

1.5.3 Laboratory Material Properties

Develop a list of material properties that each laboratory will measure. This is essential for comparing model ship test results among laboratories.

1.5.4 Field Test for Ice Properties

Develop standard field tests for measuring ice properties. Review the IAHR ice panel report to determine if their findings are applicable.

1.5.5 Voyage Measurements

Develop a set of standard measurements or observations that can be collected during a voyage.

1.5.6 Owner-Operator Cooperation

Attempt to influence ship owners to allow field testing of all vessels that have been designed, with the aid of model tests, to operate in ice. The ultimate would be to have the test program included in the vessel construction contract. This would lead to the collection of data that could be used to enhance correlation.

2. REPORT ON SUBJECTS CONSIDERED

The report of the panel makes reference to the subjects delineated in sections 1.4 and 1.5.

2.1 Bibliography

A bibliography on icebreaking vessels and related subjects was prepared by the panel and is available at the conference or from the U.S. Army CRREL in Hanover, New Hampshire. The reports in the bibliography were provided by the member organizations, SNAME MS-9 Panel and the Maritime Research Information Service (MRIS). The bibliography was edited by Ms. Nancy Dumont and Ms. Elisabeth Cole of the CRREL library. The bibliography references, articles, reports and books dating from 1968 with a few exceptions with earlier dates that were considered worthy of retention. The bibliography is categorized as follows: Resistance, Icebreaker Design, Strength Properties of Ice, Navigation in Ice, Ship Icing, Ship Mechanical Equipment, Propellers in Ice, and Ice Breaking Vessels in General.

2.2 Standardization

The ultimate objective of the panel was to recommend to the ITTC a standardization procedure for conducting model and full scale tests in ice. Although much work has been accomplished in this area, it is still in its infancy and much more work must be accomplished in order to obtain standards such as those utilized in open water testing.

This panel has reviewed what has been done over the last 20 years and has proposed a first step in standardizing model and full-scale tests in ice. The recommendations apply to the testing techniques and the presentation of the data. The analysis of the data and the exact format of full scale/model scale correlation must be studied further.

2.2.1 Introduction

Ever since the early 1950's engineers and scientists have been attempting to use model tests in ice to predict the corresponding full scale phenomena. Many techniques and methods have been utilized without any uniform acceptance and/or standardization. With the ever-increasing activity in frigid environments, some sort of guidance, direction or standardization is required in this area. The objective of the formation of the ITTC ice panel and of this report is to recommend the extent of standardization of full scale and model scale tests in ice that should be encouraged and/or required by the ITTC. Currently, the state of the art does not permit complete standardization of the scaling technique due to the lack of adequate full scale data to corroborate any particular technique in enough detail. However, the recommendations made here will form a basis for the uniform collection of the data that may eventually lead to a standard scaling technique in ice.

2.2.2 History

Currently there are some 14 or 15 organizations that are involved in testing in ice in some way or other. Some are dedicated to model testing, others are involved in full scale testing only, and still others are involved in both full scale and model testing. Table I is a summary of the results of a questionnaire sent to organizations that are involved in ice modeling. The data are presented as received; no attempt was made to verify or standardize the information. The data may have been obtained utilizing different techniques and therefore may not be comparable as presented in the table. In some cases, details of the synthetic material or wax utilized as a modeling material were held proprietary and it is not clear from the survey forms returned whether the synthetic materials simulate the temperature effect or the cohesion properties of real ice. There appears to be a proliferation of data; however, much of the data are held proprietary and are not available in the open literature for detailed scrutiny. In the past, firms such as Wartsila Shipyard (Enkvist, 1972), Arctec Incorporated (Edwards et al., 1972), the Arctic and Antarctic Institute (Kashteljan, 1968) and Hamburg Ship Model Basin (Schwarz, 1978) have tested both model and full scale vessels in ice. However, each has used a different technique or neglected to measure significant parameters. Although the amount of full scale data is limited, each claims a certain degree of success in correlating model data with full scale data, yet no standard technique is recognized. It should be noted that the current discussions are limited to non-distorted testing, i.e. the scale ratio will be constant in all directions.

2.2.3 Review of Current Techniques

Although the objectives of the techniques currently employed are identical, there is some degree of variance in the ways in which the tests are carried out. In the full scale tests, the friction factors, the ice pressure, the ship speed and other factors are measured by different methods or are omitted completely. This, of course, may lead to different conclusions (Lewis, 1972; Enkvist, 1972; Milano, 1972).

In the model regime for level ice, techniques vary widely, both in the manufacture of the model ice and the collection and interpretation of the data. There are three or four facilities that are currently conducting model tests of vessels in model ice on a continuing basis. They are Arctec Incorporated of Columbia, Maryland, and Ottawa, Canada; Hamburg Ship Model Basin (HSVA) of Hamburg, West Germany; Wartsila Shipyard of Helsinki, Finland, and the Arctic and Antarctic Institute of Leningrad, USSR. As an example of the various methods utilized, a brief description of the techniques utilized by the four facilities mentioned above is provided.

At Arctec a liquid nitrogen system is utilized to freeze the ice cover in a very short time. This leads to model ice with small crystals and the physical properties described in Table I. The model is run through the ice sheet at several speeds. The data are then regressed to obtain a predictor equation. These predictor equations do not always take the same form (see Voelker et al., 1971, and LeCourt et al., 1975).

In Wartsila the model ice is frozen using a Freon forced draft refrigeration system with seeding used to obtain smaller crystal size. The ice resistance is separated into three components: submersion, breaking and velocity-dependent components. The ice sheet is precut and the vessel moved through the ice at a very low speed to determine the submersion component. In this case only the energy needed to submerge the ice block is measured. A second ice sheet, of similar dimensions and characteristics, which is not precut, is used to determine the combined submersion and breaking. The vessel is then run through this ice sheet at low speeds to obtain the submergence and breaking energies (resistances). The submergence resistance is then subtracted from the total to obtain the breaking resistance, which is then corrected for the proper $\frac{E}{\sigma}$ value to maintain the correct scaling of the breaking term. The vessel is then run at desired speeds into an uncut ice sheet and the total resistance is measured. The resistance due to submergence and breaking is subtracted to obtain the inertial component of the resistance. These three components are then summed in a linear fashion (see Enkvist, 1972) and scaled by λ^3 to obtain the full scale resistance.

The HSVA tank utilizes a technique put forth by Schwarz (1975). The refrigeration system is a Freon natural convection system. In this technique the ice sheet is grown at -14°C and seeded to obtain proper crystal size. Then it is stabilized at approximately -1°C to obtain a proper elastic modulus. The model ice physical properties are shown in Table I. HSVA prefers to utilize a geometric scale ratio of $\lambda \leq 20$ and has limited the flexural strength of the saline ice to $\sigma_f \geq 50$ kN/m^2. Within these limits the model resistance is then scaled by λ^3. For scale ratios greater than 20 and strength values less than 50 kN/m^2, additional tests are conducted at larger strength values and the model results are graphically extrapolated to the required strength. The corrected resistance is then scaled by λ^3.

The Arctic and Antarctic Institute utilizes still another technique (Kashteljan et al., 1968). Ice sheets are grown (using seeding to control crystal size) with the properties described in Table I. Models are tested at very low velocity and the resistance scaled up to λ^3. To this resistance is added an additional term that reflects the influence of the velocity (inertial) effect. The last term is an empirical term derived from experience with full scale vessels.

Thus, it can be seen that in the four facilities that are involved in model testing in ice, there are four different techniques being utilized. Each technique has its advantages and disadvantages. It is difficult, if not impossible, at this time to state which technique is the recommended technique for a given condition; however, several basic procedures can be followed and measurements taken in order to standardize the data obtained. Standardization of interpretation and utilization of the data will take more research and full scale tests.

2.2.4 Basic Measurements

In order to establish a base for any standardization of full scale and model scale tests, the significant parameters involved in the process must be delineated and a set procedure for obtaining these parameters spelled out. The significant parameters involved in a vessel's motion through ice can be broken down into two categories, one dealing with the environment, the second dealing with the vessel. Table II and Table III list the parameters that must be determined and the relative priority of each, i.e. Priority 1 indicates those parameters that must be measured in order to utilize any of the data for correlation, Priority 2 those that will add to the usefulness of the data, and Priority 3 those that may be of use at some later date or for some other area of research. The techniques utilized to obtain these parameters will be discussed in another section of this report.

2.2.5 Standardization of Scale Model Tests

While full scale trials are carried out with similar techniques, model tests vary from establishment to establishment. Different ice modeling materials have been used as well as different techniques. However, there is agreement on the laws of similitude that must be satisfied. Basically, these reflect the satisfying of the Froude number and the Cauchy number. Currently no corrections are made for Reynolds number effects.

2.2.5.1 Scaling Requirements

Of considerable importance is the scaling of the modulus of elasticity and the flexural strength (or any strength property for that matter) by λ. This requirement leads to the relationships:

$$\frac{E_p}{E_m} = \frac{\sigma_p}{\sigma_m} = \lambda \qquad (1)$$

or

$$\frac{E_p}{\sigma_p} = \frac{E_m}{\sigma_m} \qquad (2)$$

As can be seen from Table I many of the establishments' procedures do not satisfy this relationship. The full scale ratio of E_p/σ_p is of the the order of 3000 to 5000 while many model ice ratios are of the order of 300 to 500. This results in a highly plastic ice that deflects to a greater extent than does the natural full scale ice. Whether the energies of fracture and low velocity submergence are respectively exchanged giving the same total energy is not yet fully determined. The significant fact is that the elastic modulus of the model material must approach that of the natural ice.

In addition to the strength, modulus and thickness, for saline ice the crystal size should be reduced as far as possible to approach the proper scale size. If special techniques are not utilized, the crystal size of the model ice may get to

Table I. Specifics of Ice Modeling Basins.

PROP / BASIN	UNITS	SYM-BOL	Basins Using Saline Ice						Basins Using Synthetic Ice or Wax				
			ARCTEC INC.	ARCTEC CANADA	AAI	WARTSILA	CRREL[1]	HVSA	OTC	NRC CANADA	NSMB	BHC	ARCTEC CANADA
FLEX. ST.	kPa	σ_f	5-70	7-138	15-98	15-100		≥ 50	>20	30-100		48	7-138
MOD. OF EL.	kPa	E	$5\text{-}140\times10^3$							$4\text{-}8\times10^4$		130×10^3	
MOD. RATIO		E/σ_f		1000-2000				1500-2000	2000	∿1000			1000-2000
SPECIFIC GRAV.		S	.940	.910	.880-.900	.900		.900	.900	∿.910	.800-.900	.850	.91
FRICT. COEF.		μ	.02-.50	.10-.60	.08-.11	.030-.34		.050-.40	.30	.17-.20		.04-.20	.10-.60
ICE THICK	mm	h											
Level			7.5-254	7.5-114	7-85	10-65	5-600	20-100	YES-NVG	≤ 30		YES-NVG[2]	7.5-114
Clogged			7.5-100	7.5-222	10-30	10-300	YES	YES-NVG	YES-NVG			YES-NVG	7.5-222
Ridged			300-500	102-457	NO	500	YES	300	YES-NVG		NO		102-457
Mush			25-100	7.5-114	10-35		YES	20-60	NO		NO		7.5-114
Floe			7.5-254	25-457		10-65	5-600	NO	YES-NVG	≤ 30		YES-NVG	25-457
SC. FACT. RA.		λ	10-100	10-120	10-60	5-72		15-48	40-100	8-40	15-80	30-40	10-120
BASIN LEN.	m	ℓ	30.0	30.5	13.4	29.0	36	30.0	89.9	30.0	100&220	76.2&24.4	18.9
BASIN WID.	m	w	3.65	4.9	1.85	4.8	9.2	6.0	14.6	6.0	24&16	3.7	6.1
BASIN DEP.	m	d	1.50	1.8	1.3	.82-1.05	2.5	1.2	4.6	1.2	2.5&1.2	1.7	.9
MAX. MOD. LEN.	m	L	6.86	6.1	2.85	9.0	6.0	9.0	9.14	8.0	12.0	4.88	6.1
MAX. MOD. BEAM	m	B	1.50	.91	.56	1.2	2.0	1.2	1.22	1.2	2.0	.76	.91
MAX. MOD. DRAFT	m	T	.35	.91	.22	.5	1.0	.4	1.0	1.0	.8	.46	.91

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[1] Tank will be operational in 1978.

[2] NVG – No Value Given.

Table I (cont'd)

			Basins Using Saline Ice						Basins Using Synthetic Ice or Wax				
BASIN PROP	UNITS	SYM-BOL	ARCTEC INC.	ARCTEC CANADA	AAI	WARTSILA	CRREL[1]	HVSA	OTC	NRC CANADA	NSMB	BHC	ARCTEC CANADA
MOD. MAT.			W	W-S-FG-SF	W-PL	W-FG	W-S-AL	W-FG	W-PL-ST-AL	W-FG	W-FG	W	W-S-FG-SP
SURF. TREAT.			SANDED	TEF-PAINT	SP PAINT	SP COAT	SP PAINT	PAINT COAT	PAINT	SP PAINT	SP PAINT	SP PAINT	PAINT
SIM. ICE MAT.			SL ICE	SL-ICE	SL ICE	SL ICE	SL ICE	SL ICE	SYN	SYN	WAX	WAX	WAX
FR. TEMP.	°C		-50 to -100	-54	-12	-18	-30	-15	NA	NA	NA	NA	-
OP. TEMP.	°C							-1					
MAX. GR. RA.	mm/h		10	6.4	1-3	3	2	2	NA	NA	NA	NA	-
ICE SH. PRO.	per 5 day wk		10	5	5-6	5	5	3-5	2	4		7.5	5
SNOW SIM.			NO	NO	NO	NO		NO	NO	NO	NO	NO	YES
NO. MOD. TEST			65	16	147	60		20		12			16
COMP. ST.	kPa	σ_c	5-45	17.5-345		45-300		260				151	17.5-345
TYPE OF TEST													
RESIST			YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
CONST. SP.			YES	YES	YES	YES	YES	YES	YES	YES	YES		YES
CONST. FORCE			YES	YES	YES	YES	YES	NO	YES	YES	YES		YES
SELF PRO.			YES	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
MANOEU.			YES	YES	NO	YES	YES	YES	YES	NO		YES	YES
ICE LOADS			YES	YES	YES		YES	YES	NO	YES	YES		YES
PROP. INT.			YES	YES	YES	YES	YES	YES	YES	YES		YES	YES
COMP. ICE (LATERAL)				YES		YES	YES	YES					YES

Table I (cont'd)

BASIN / PROP	UNITS	SYM-BOL	Basins Using Saline Ice						Basins Using Synthetic Ice or Wax				
			ARCTEC INC.	ARCTEC CANADA	AAI	WARTSILA	CRREL[1]	HVSA	OTC	NRC CANADA	NSMB	BHC	ARCTEC CANADA
PILES					YES	YES	YES	YES					
BUBBLERS			YES	YES	YES	YES	YES	YES		YES			YES
HEEL AND PITCH			YES		YES	YES	YES	YES	YES	YES			
WATER JET						YES	YES	YES					
HOVER CRAFT				YES		NO	YES	NO					YES

NOTE: The data in this table are presented as received; no attempt has been made to verify or standardize the information. The data may have been obtained utilizing different techniques and therefore may not be comparable as presented. In some cases, details of synthetic materials, utilized as modeling materials, were held proprietary and it is not clear whether these materials simulate the temperature effect or the cohesion properties of real ice.

FACILITIES

Arctec, Incorporated Columbia, Maryland USA	(ARCTEC, Inc.)
Arctec Canada Limited Ottawa, Ontario CANADA	(ARCTEC Canada)
Arctic and Antarctic Research Institute Leningrad USSR	(AAI)
Experimental and Electronic Laboratory British Hovercraft Corp. Isle of Wight ENGLAND	(BHC)
U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire USA	(CRREL)
Hamburg Ship Model Basin Hamburg WEST GERMANY	(HSVA)
Offshore Technology Corporation Escondido, California USA	(OTC)
Marine Dynamics and Ship Laboratory National Research Council Ottawa, Ontario CANADA	(NRC Canada)
Netherlands Ship Model Basin Wageningen NETHERLANDS	(NSMB)
Wartsila Ice Breaking Model Basin Oy Wartsila Ab Helsinki Shipyard Helsinki FINLAND	(Wartsila)

Table II. Environmental Parameters to be Measured* in Ice Breaker Testing (Both Field and Laboratory).

Parameter	Priority
Ice Thickness	1
Ice Temperature Profile	1
Ice Salinity Profile	1
Snow Cover Thickness	1
Ice Pressure	1
Pressure Ridge Profile (Depth and Length)	1
Broken Channel Size and Percent Coverage with Broken or Mush Ice	1
Elastic Modulus (Lab Only)	1
Qualitative Description of Environment	1
Ice Floe Size and Percent Coverage	1
Qualitative Description of Ice Profile and Type	1
Ice Density	1
Snow Density	1
Ice Flexure Strength (Lab Only)	1
Ice Crystal Size	2
Ice Tensile Strength (Lab Only)	2
Ice Compressive Strength (Lab Only)	2
Ice Shear Strength (Lab Only)	2
Wind Speed and Direction (Field)	2
Air Temperature	2
Current Speed and Direction	2
Water Depth	2
Cusps Length and Width	2
Photographic Documentation of Ice Patterns	3
Seawater Temperature and Salinity	3

* The techniques and required accuracy of these measurements are covered in another section of this report.

Table III. Vessel Parameters to be Measured in Ice-Breaker Testing (Both Full Scale and Model Regime).

Parameter	Priority
Vessel Particulars (Complete Definition of the Vessel, i.e. Lines Drawings)	1
Ship Speed	1
Shaft Thrust	1
Shaft Torque	1
Shaft RPM	1
Ice-Hull Coefficient of Friction Dynamic (with and without snow; Wet and Dry)	1
Ice-Hull Coefficient of Friction Static (with and without snow; Wet and Dry)	1
Propeller Pitch	1
Vessel Draft Fore and Aft	1
Penetration Distance on Ram	1
Heeling System Utilized	1
Bubbler System Utilized	1
Trim System Utilized	1
Photographic Documentation of Ice/Ship Interaction	1 1
Total Resistance Towed Model (Dynamometer Reading - Model Scale Only)	1 1
Total Thrust Self Propelled Model	1
Turning Circle Radius	1
Time History of Above Events During Testing	1
Hull Roughness	2
Vertical Acceleration (Fore and Aft)	2
Horizontal Acceleration (Fore and Aft)	2
Pitch Angle	3
Roll Angle	3
Rudder Angle	3
Rudder Torque	3
Propeller Blade Bending Moments (Full Scale Only)	3
Propeller Pitch Torque (Full Scale Only)	3
Hull Strain Gages (Full Scale Only)	3
Propulsion System Monitoring Sensors (Full Scale Only)	3
Propeller RPM in Open Water	3
Propeller RPM in Ice Clogged Waters	3
Wake Survey in Ice	3
Wake Survey in Open Water	3

be very large and will affect the breaking patterns and strength.

Other significant factors are the coefficient of friction of the model and model ice and the ship and full scale ice. The laws of similitude require the coefficients to be equal. Early researchers neglected this effect; however, recent work has stressed this area of similitude.

With these points in mind the standard model test then should be conducted in model ice that adheres to the laws of similitude in Table IV.

Ice sheets should be prepared to assure proper crystal size, either through seeding or through rapid freezing techniques. The ice sheet should be as uniform as possible. A 15% variation in ice thickness within a test run is considered high.

Table IV. Similarity Relations for Modeling Vessels in Ice.

Length	$= L_p = \lambda L_m$
Beam	$= B_p = \lambda B_m$
Draft	$= T_p = \lambda T_m$
Force	$= F_p = \lambda^3 F_m$
Displacement	$= \nabla_p = \lambda^3 \nabla_m$
Velocity	$= V_p = \sqrt{\lambda} V_m$
Time	$= T_p = \sqrt{\lambda} T_m$
Gravity	$= g_p = g_m$
Thickness	$= h_p = \lambda h_m$
Flexural Modulus	$= \sigma_p = \lambda \sigma_m$
Elastic Modulus	$= E_p = \lambda E_m$
Coefficient of Friction	$= f_p = f_m$
Viscosity	$= \nu_p = \nu_m$
Density of water	$= \rho_{wp} = \rho_{wm}$
Density of Ice	$= \rho_{ip} = \rho_{im}$
Poisson's Ratio	$= \mu_{pp} = \mu_{pm}$

p = prototype; m = model; and λ = geometric scale factor.

2.2.5.2 Tank and Model Sizes

The tank utilized should be large enough to allow at least three characteristic lengths between the point of application of the ice load, i.e. the bow of the vessel, and the extreme boundary. The characteristic length of an ice sheet is the distance at which edge effects are negligible and the sheet can be considered an infinite sheet. The characteristic length (ℓ) is defined by the following relationship:

$$\ell^4 = \frac{E\,h^3}{12\,(1-\mu_p^2)\,\gamma_w} \qquad (3)$$

where ℓ = characteristic length in meters

h = ice thickness in meters

E = ice modulus of elasticity in pascals

μ_p = Poisson's ratio

γ_w = specific weight of water in newtons per cubic meter

As a rule of thumb, to simulate unrestricted ice boundaries and deep water conditions at low speeds, tank width should be at least 6 times the characteristic length for continuous ice sheets and the tank depth should be greater than $D = 3\sqrt{BT}$, where D is depth in meters, B is the model beam in meters and T is the model draft in meters. The tank should be long enough to allow at least one full ship length of penetration at steady state for each resistance data point obtained. The speed of the carriage for resistance tests should be maintained to within ±.02 mps and the resistance readings should be measured to within 0.5%. Due to the uncertainties of scale effects, large scale ratios should be avoided and geometric scale ratio should not exceed 50 if possible; however, scale ratios in the area of less than 30 are preferred.

The results should then be presented in such a way that all the parameters delineated in Tables II and III are readily available for analyzing the test results.

2.2.5.3 Testing Techniques

When the correct thickness, strength and modulus of the ice sheet are obtained, the model is set to the correct displacement and trim and every effort should be made to set the longitudinal radius of gyration to the values established by the ITTC Seakeeping Standards. In towed model tests, the carriage is run at a steady speed through the ice sheet for at least one full model length, the speed can then be increased and another data point obtained. Care should be taken to ensure that steady state is achieved at the trial speed. A certain amount of replication is recommended to insure the statistical reliability of the data obtained. Statistical design techniques should be employed to obtain the greatest utility from the data. The statistical techniques and extent of replication are matters best determined by the researcher.

Upon completion of the level run ice tests, the broken ice can then be utilized for the broken channel ice test. In these tests, the procedure is similar to that for the level ice except that the model should be run through at least two model lengths of broken channel. The critical measurement in these tests is the degree that the channel is filled with ice. One should ensure that for a channel 100% filled with broken ice, no open water patches are visible. Lesser degrees of ice in the channel should be documented with overhead photographs and movie film or video tapes.

In general, model tests of ice fields under pressure and ice fields with ridges or hummocks are in the initial stages and more must be done in the various tanks throughout the world to standardize techniques and quantify results and compare these results with full scale data.

2.2.5.4 Self Propelled Testing

Some model tests have been performed in saline and synthetic ice using self propelled models. Whereas the towed tests are conducted to determine the effectiveness of the hull form in breaking and progressing through ice, the self propelled tests are conducted to determine the effectiveness of the total system, i.e. hull and propeller.

The tests are carried out by fitting the model with propellers and dynamometers that measure torque, thrust, and rpm. (The propellers may be stock model propellers that have the approximate full scale propeller characteristics.) The model must be free to heave, pitch and roll as it transits the length of the tank. This can be accomplished with an umbilical cord trailing from the towing carriage, through the use of telemetery systems, or directly from the carriage using differential dynamometers. A rudder and rudder control mechanism should be installed to control the direction of the model if the model is not guided by the carriage. Upon proper ballasting and trimming the model is run the length of the tow basin in open water at various speeds. These tests should be carried out at the model self propulsion point, the ship self propulsion point, and overload conditions. Analysis of the data will yield an estimate of the quasi-propulsive coefficient in open water.

The self propelled tests described above are then repeated in ice, either level ice or broken channel ice and the same data collected. These data will yield an estimate of the quasi-propulsive coefficient in an ice environment. Thus such self propelled tests will yield the effectiveness of the total ship propulsion system, i.e. hull form and propeller-hull interaction. Many researchers feel that the self propelled tests are the more significant tests in evaluating a ship's performance in ice.

Due to the more critical nature of the Reynolds effects in propeller interactions, it is recommended that the tests delineated above be carried out following ITTC recommendations for self propelled tests in open water. The larger model and the smaller scale factor will yield more reliable results.

At the current level of technology in the modeling of vessels in ice, maneuvering tests can only be considered qualitative in nature. Work has to be done on the potential of the use of the planar motion mechanism in longitudinal tanks and work has to be initiated in larger basins that can have the model make a complete 360 degree turn in ice. Due to the larger ships being proposed and the requirements for maneuverability in smaller vessels in lakes and rivers, there is a growing need for the undertaking and standardization of such tests.

Another area that should be investigated is the performance of propellers themselves in ice infested waters. The following technique can be utilized to determine the effect of ice on propeller performance.

The propellers may be first tested in open water with no ice. This can be accomplished in a towing basin or in a flume or circulating water channel to determine their open water efficiency in the conventional manner, i.e. by measuring the torque, thrust, and rpm at specific speeds of advance. The tests are then repeated with ice blocks of various sizes in the water. Here one must use discretion as to the extent, i.e. number and frequency, of ice blocks reaching the propeller. It would be useful to observe the ice flow patterns under the model in the towed or self propelled tests before conducting the propeller tests. The difference in efficiency in ice-free water and ice-infested water would then give an indication of the effect of ice on propeller efficiency.

2.2.6 Standardization of Full Scale Test

In order to assure that similar and useful data are obtained in full scale tests at least the number 1 priority parameters of Tables II and III should be measured as described in the following section of this report. The basic objectives of full scale tests should be:

- determination of maximum ice thickness in which the given ship is capable of continuous movement using full power;
- determination of the speed of advance in ice of different thicknesses and conditions, i.e. pressure ridges, brash ice and mush ice;
- checking of data obtained during the ship model tests in the model tank;
- accumulation of information for development of objective design criteria on the interaction of icebreaker hull, propellers and rudder with ice;
- determination of ship operating characteristics;
- obtaining data necessary to increase the accuracy of the theoretical calculations of ship performance.

2.2.6.1 Trial Site and Ice Conditions

The above-mentioned objectives can be achieved if there are suitable ice conditions in the areas in which trials will be performed. Suitable ice conditions are those in which all characteristics can be measured using special instrumentation. The following ice conditions fully or in part meet this requirement:

- unbroken ice of constant thickness as described below;
- a channel broken by the icebreaker in unbroken ice of constant thickness;
- ridges;
- channels partially filled with broken or brash ice.

When trials are carried out in ridges, the morphology of the ridges should be defined as completely as possible. Sail height, width, frequency and spacing is the minimum information that should be recorded. Where conditions and equipment permit, the submerged and sail profile and characteristics should be measured.

When selecting possible areas for ice trials, the following items should be taken into consideration.

Shallow water can affect the trial results. Therefore, for deep water tests the water depth in the area of the trials is to be not less than the value estimated by the 12th ITTC for ship trials in ice-free water:

$$D = 3.0\sqrt{BT} \qquad (4)$$

where D = water depth in meters
B = ship beam in meters
T = ship draft in meters

If the ice conditions in the area chosen are such that the ship will not advance with a speed of more than 3-4 knots, then water depth equal to 2.5 ship drafts can be considered sufficient.

If one of the ice trial objectives is checking the ship's ability to navigate through ice in shallow water, then it is necessary to check to what degree the water depth in the trial area remains constant.

Lateral ice pressure can have a significant effect upon ice resistance to ship motion. Therefore, it is desirable for the trials to be conducted in shore-fast ice or in large ice floes. The site where the trials are to be conducted should preferably be on the leeward side of islands, or in straits or bays.

Due to the potentially large effect of ice pressure, it is desirable to develop means to measure it quantitatively. Currently, one indication that ice pressure exists is when the track closes behind the vessel. In these cases, it is suggested that a record be kept of the closure rate of the channel in order to obtain some idea of the order of magnitude of the lateral pressure. The current state of the art does not provide for further refinement of ice pressure definition and measurement at this time.

2.2.6.2 Continuous Motion Tests in Sheet Ice

In continuous tests satisfactory tracklines should be selected and ice thickness measurements made before the test run if possible. The trackline of the run is considered to be satisfactory if a systematic variation of ice thickness along it does not significantly exceed that of the mean value (approximately ± 10%). Several tracklines can be used in the trial area. The distances between the tracklines are to be large enough so that ice cracks are not initiated in the vicinity of the previously broken channels.

After selecting the trackline and after determining the sequence of its passage, the ship is stopped in the ice at the starting point.

The trials begin with the determination of the starting icebreaking thrust in ice of a given thickness. For this purpose the propeller revolutions per minute (rpm) and/or propeller pitch are increased successively step by step, typically every 15 seconds, and the total thrust, torque and rpm at which the ship just begins to move are determined.

When the ship does not stop but continues to move until her speed becomes steady, all ship data are recorded over a distance of about two ship lengths.

Propeller rpm and/or pitch are successively increased so that the power increases in approximately equal steps. The ship parameters are then measured at steady speed and at constant power settings over two ship lengths in four to six increments of the trackline. The tests are completed after steady speed is achieved using maximum power. After the ship passes each increment of trackline, at the increments of steady speed of ship advance, measurements of ice and snow conditions are made. Simultaneously, wind and current velocities and directions as well as air temperatures are measured.

On one side of the trackline, measurements of ice and snow density and profiles of temperature, salinity and ice thickness are carried out. This information is used to define the characteristics of the ice.

It is desirable to investigate ice structure and strength for each trial site using the methods described in section 2.3 of this report and in the stated references.

The surface roughness of the ship's hull has a significant effect upon the steel-ice friction coefficients and therefore upon the speed of advance. The hull roughness value should be measured in the region of the water line during the trials and over the entire bottom of the ship at the next dry docking. The static and dynamic steel or hull coating-ice friction coefficients should be measured as recommended in section 2.2.8.1 of this report. Ice friction coefficient as a function of ice and hull temperature, specific presin the contact zone, relative velocity, and hull surface roughness are subjects for future investigation.

Test results for each trial site are presented in the form of ship speed vs. thrust and ship speed vs. power at constant ice thickness.

The analysis of test results makes it possible to define the total ship thrust and/or power as a function of ice conditions such as thickness, strength, and pressure, and ship characteristics such as speed.

For the total ice resistance value in the case of steady ship movement the following expression is taken:

$$R_{TI} = \Sigma\, T_{pi}\ (1 - t_i) \tag{5}$$

where T_{pi} = thrust of each propeller averaged for a run;

t_i = thrust deduction coefficient based upon resistance and self propulsion conducted in ice

2.2.6.3 Ramming Tests in Sheet Ice

The objective of ramming tests is to determine the ship's ability to move through ice of greater thickness than it could in the continuous mode.

The parameters measured are the same as those for the test of continuous ship movement in level ice.

Before performing ice trials in the selected area, it is necessary to insure that the ice on the course is thicker than that that can be broken in the continuous mode. The ship is backed out of the ice far enough to assure adequate velocity upon impact, then, with full power, is rammed into the ice cover. The engine power level is not changed until the ship stops. The moment when the stem of the ship touches the unbroken ice cover is recorded, along with ship speed and the other parameters mentioned in the previous sections. The speeds of the subsequent rams are increased by increasing the acceleration distance. Four or five rams are typically performed.

The test results are presented in the form of the relationship between the distance of penetration into the ice and the ship's speed from the moment the stem touches the unbroken ice cover. The distance of penetration is determined by direct measurement or by integrating the ship speed - time relationship.

Analysis of the test results makes it possible to approximate the resistance of the ice to the ship's motion at ice thicknesses greater than the maximum continuous permissible value:

$$R_{TI}\ (v) = \Sigma\, T_{pi}\ (v)\ [1 - t_i\ (v)] + kma\ (v) \tag{6}$$

where a (v) = longitudinal ship acceleration determined by differentiating the speed - time relationship;

m = ship mass;

k = coefficient of mass and entrained mass of water and ice.

2.2.6.4 Broken Channel Tests

The objective of broken channel tests is to determine the speed of advance of the ship as a function of engine power, thrust, ice thickness, percentage of the channel filled, and average size of ice pieces. In addition to the previously obtained characteristics of the ice cover, the size of the ice pieces in the broken channel and their compactness are also determined. Aerial photographs of the broken channel taken from helicopter before and after the tests would aid in documenting the broken channel condition.

In a channel of broken ice, 3-4 runs are performed at steady speed at different constant power levels.

Test results at various sites make it possible to determine the approximate total ice resistance of the ship in a channel as a function of ice thickness, percent coverage and speed of advance.

2.2.6.5 Ridge Tests

Ship trials in ice ridges are performed with the objective of determining the size, frequency and spacing of ridges that can be penetrated by the ship in one or more rams, in addition to the ship's resistance to motion.

In addition to the values measured during the tests in level ice, it is suggested that the following ridge characteristics be determined:

- sail heights;
- keel depths;
- profiles of the top and bottom surfaces;
- structure;
- size of ice blocks;
- age.

The profile of the top surface of the ridge can be measured using geodesic methods. The profile of the bottom surface can be measured using a sonar submerged in holes in the ice cover drilled from the two sides of the ridge, or can be estimated from ridge sail dimensions.

The ship rams the ridge along a line perpendicular to it at a predetermined impact speed. When the ship comes to rest, the penetration distance is measured. Then the ship backs out into the channel and repeats the procedure until the ridge is penetrated. When the ship penetrates the ridge, it stops after the whole hull passes through the ridge and additional ridge data are obtained. The tests would typically be repeated 5-10 times in different ridge configurations using full power and various acceleration distances. The test results are presented in the form of the relationship between the loss of ship kinetic energy and the geometry of the ridge damaged or penetrated.

The loss of ship kinetic energy per ram is determined by the formula:

$$E = \frac{V_1^2 - V_2^2}{2} mk + \frac{(T(V_1) + T(V_2))}{2} S \quad (7)$$

where V_1 = ship speed at the moment the ship's stempost touches the ridge;

V_2 = minimum speed when the ridge is penetrated or zero if the ship is stopped in ramming;

S = penetration distance.

The geometry of the ridge destroyed should be determined.

The test results can be used to determine the speed of advance required to pass through ridges of given sizes and frequencies.

The ship resistance can then be determined using equation (6).

2.2.6.6 Voyage Tests

The objectives of ship tests during operational voyages are as follows:

- obtaining data on ship speed under various ice conditions;
- determining the effect of seasonal change in ice properties on the results of the ice trials.

Data recordings should be made for appropriate periods at intervals determined by variations in the environment. In all cases the length and number of recordings should be sufficient for analysis and to describe conditions, but they should not be so long and numerous as to make analysis unduly burdensome or impossible. The data should be recorded with proper instrumentation, however, if specific instrumentation is not available, estimates should be made using the equipment available.

Non-uniformity in ice thickness is the cause of non-uniformity in speed of advance; therefore, when collecting voyage data it may be necessary to average ship speed over larger distances than during the ship ice trials. Typically the average ship speed developed at a given power setting over a distance of one nautical mile may be used as the speed in that particular environment.

The ship speed in specific ice conditions would typically be determined for one or two power levels.

In fast ice the ship speed in ice conditions is dependent upon

- ice and snow thickness;
- hummocking of ice;
- the degree of ice deterioration;
- ice pressure (lateral)
- power level;
- ice strength;
- vessel parameters, including friction.

In pack ice the ship speed in ice conditions is dependent upon

- ship parameters, including pitch;
- ice and snow thickness;
- percent of ice coverage;
- hummocking of ice;
- degree of ice deterioration;
- size of ice pieces;
- ice pressure (lateral);
- power level;
- ice strength.

All ice properties are averaged over the same distance as that over which the speed is averaged.

During operational voyages all ice cover properties are determined without the ship stopping her engines, by using instrumentation or observation by experienced personnel.

Obtaining sufficiently complete data to estimate the effect upon the ship speed in various ice conditions of each one of the above-mentioned ice characteristics (the rest of which are constant) requires accumulation of a great number of measurements.

All data obtained during ship voyages may be processed on the basis of mathematical statistic methods, and are presented in the form of the ship speed in ice conditions as a function of the ice thickness and the ice cover characteristics.

The importance of occasional stops to obtain ice data cannot be over-emphasized; otherwise the scientific usefulness of the data will be limited.

2.2.7 Analysis of the Data

Due to the emerging state of the technology it is recommended that all reports be prepared in such a way that all the data measured are made available for detailed analysis. The measured data should be in tabular form for each run, indicating the parameters delineated in Tables II and III. Although the priorities indicated in the tables should be adhered to, it is essential that the parameters of elastic modulus of the model ice, flexural strength of the model ice (or temperature and salinity profiles of the full scale ice), coefficient of friction of the model and full scale regime, and depth of snow be particularly recorded. All data should be presented in SI units.

The data should be presented as originally collected, without reduction to any non-dimensional parameters. Some researchers favor certain combinations of terms in a non-dimensional form; however, there has been no universal agreement on which combination is the most meaningful. Until the subject is studied in more depth by the ITTC and such an agreement is reached, the data should be presented as collected, and the formation of non-dimensional parameters left to the discretion of the individual researcher.

The symbols that are utilized in ice work are becoming more universal and are used in Table I with few exceptions. They reflect the standard symbolism utilized in Naval Architecture, Ice Mechanics and ITTC.

At the present time a universal resistance equation that can be used for making ship resistance predictions based on model tests in ice cannot be agreed upon. For level ice with no snow cover, some researchers have grouped the resistance into three terms, one a function of the fracturing of the ice, the second a function of submerging of the ice, and the third a function of the velocity of the vessel. The terms are linearly independent and can be summed (with appropriate modification and/or correction) to determine the total resistance, i.e. R_I =

R_{IB} (σ_f, h, B) + R_{IS} (ρ_i, ρ_w, g, B, h, T) + R_{II} (ρ_i, B, V, L, h). The difficulty here is in determining the exact combination of the variables and the effect of pressure, friction and lack of exact similitude in each of the terms. Specific effects in the change of hull form are included in the coefficients of the predictor equation due to the model being geometrically similar to the full scale ship.

Before such an equation can be standardized much more must be done to investigate the effects of changes in the various parameters. In addition, investigation into the form of such equations in brash and mush ice, as well as pressure ridges, must be undertaken. Once such standardization is justified, it will apply equally well to the full scale and the model scale regimes. Each term should relate to some physical aspect of the phenomena that are occurring, i.e. breaking, submergence, etc., similar to the two components of the traditional open water resistance equation.

2.2.8 Full Scale/Model Scale Correlation

With the adherence to the scaling laws delineated in the previous section, satisfaction of the Froude and Cauchy number will mean that the overall resistance of the model can be scaled by λ^3 to obtain the total resistance of the prototype. The difficulty here lies in the fact that, normally, the model tests do not satisfy all these conditions.

To facilitate the comparison of full scale and model scale data a standard resistance equation such as was discussed in the previous section should be utilized. Agreement on the form of the equation would permit the researcher to regress his data to obtain a least squares equation for both the model and full scale data that would facilitate correlation of the data obtained and facilitate analysis of the various components of the overall resistance. Until more work is done in this area, no uniform recommendation on correlation can be made at this time.

2.2.8.1 Measurement Techniques

The measurement techniques that should be utilized to determine the majority of the parameters delineated in Tables II and III are discussed in section 2.3 of this report, particularly the field and laboratory measurement of ice parameters. However, there are a few parameters that deserve specific comment due either to the various techniques used to obtain them or to their importance in the final utilization and analysis of the data.

One of the most important parameters is vessel speed. In full scale tests it is suggested that the speed measurement be made by more than one method. The simplest method is that of visual sightings, either by the chip log method, where a standard distance is measured on the vessel and the time for a specific object to pass the standard distance is measured, or conversely by placing poles at set distances on the ice along the trackline and noting the time required to traverse the distances. An alternate method consists of using a doppler radar that is installed on the ship and utilizes targets of opportunity on the ice cover. A third method, and the most accurate, would be the utilization of a radio position fixing station such as the Decca or Mini-Ranger System. This method would involve placing two transponders on the ice cover with a main unit on the vessel. It would be the most accurate and could also be used to determine the maneuvering characteristics of the vessel by keeping track of its position as well as its speed. Other methods, such as low light level T.V., sonar systems, doppler boundary layer log, and a taut trailing wire system, can also be used. All these systems should feed to the main data recording station.

In the towing basin measuring vessel speed is much less of a problem and can be accomplished by monitoring carriage speed.

Thickness is an important parameter in determining ship resistance and therefore should be carefully measured along the trackline using coring devices at random intervals. In addition, continuous measurements along the trackline may be made utilizing an impulse radar device. In the towing basin ice thickness is determined by cutting the ice sheet at its edge and by measuring ice thickness at the broken channel edge.

One of the most difficult parameters that must be measured is the hull-ice friction coefficient. The friction coefficient should be measured as realistically as possible. One method (LeCourt et al., 1975) would be to cut blocks of ice from the ice cover and drag them along the vessel's hull above and below the waterline with the device described by LeCourt (1975). An alternate method would be to draw ice over a steel plate coated in the same fashion as the hull of the vessel, recording the normal and tangential forces. The roughness of the hull should be measured utilizing a materials roughness measuring device and correlated with the friction coefficient. Similar measurements should be made in the towing basin, i.e. drawing an ice block along the model hull or plates of model material, and measuring the model coating roughness.

Another parameter that must be measured with care and some redundancy is the vessel thrust. Many of the existing techniques such as thrust blocks, rpm readings and strain gauges on the shaft have met with varying degrees of success and should be carefully utilized. It is recommended that thrust meters and torque and rpm monitors be installed on all new icebreaking vessels. In the model regime, the rpm, thrust and torque are measured with the proper dynamometers on the model and on the carriage.

Measurement of the remaining parameters is either discussed in section 2.3 of this report or is fairly self-explanatory.

2.3 Ice Properties

One of the major problems in conducting full scale resistance tests is the difficulty in measuring the ice strength and elasticity. The most common field test for determining the flexural strength of ice is the cantilever beam test. It is very difficult to perform once the ice thickness exceeds 50 cm. At this time another means of determining the flexural strength has to be used.

It has been well established that the strength of sea ice is related to its brine volume ν, which is a function of the salinity and temperature of the ice. Brine volume can be computed by

$$\nu = \frac{S}{1000} \left(\frac{49.185}{Q_i} + 0.532\right) \qquad (8)$$

where S is the salinity of the ice in parts per thousand and Q_i is the negative ice temperature in degrees Celsius. The salinity and temperature are easily obtained by collecting core samples of the total ice thickness. The core can then be cut into small samples. The ice temperature of each sample should be measured as soon as possible after extraction from the ice sheet. The salinity can be measured once the sample has been melted.

An approximation of the flexural strength σ of the ice can then be calculated from the following equation:

$$\sigma = \sigma_o [1-\sqrt{\nu}]^2 \qquad (9)$$

where σ_o is a constant and has a value of approximately 7.0 based on actual tests.

The elastic modulus of thick sea ice is difficult, if not impossible, to measure but its approximation may be calculated from the following equation:

$$\frac{E}{E_o} = (1-\nu_b)^4 \qquad (10)$$

where E_o is a constant and has a value of approximately 10.0×10^{10} dynes/cm^2. The elastic modulus may also be estimated by comparing with published dynamic values if the volume of brine has been determined.

It is very difficult to measure the density of natural ice, especially under field conditions. For full scale resistance tests the density of the ice can be estimated at .91 g cm^{-3} to .92 g cm^{-3} for fresh water ice and .88 to .90 for sea ice. In the laboratory the density of the model material may be estimated by displacement or by weight volume measurements.

Strength measurements conducted in the laboratory are relatively easy to perform when compared to full scale tests. Again, the most common test for estimating the flexural strength is the cantilever beam. Working with thin laboratory ice care must be taken in preparing the beam so that flooding is kept to a minimum. If not the true strength value will be much greater than the measured one. Flooding of thin ice causes the temperature to increase which in turn results in a lower strength value.

The elastic modulus can be estimated by measuring the load and deflection of the ice sheet simultaneously. From this the radius of influence ℓ can be determined by

$$W = \frac{P}{8\gamma_w \ell^2} \qquad (11)$$

where W is the deflection, P is the load, and k is the density of the water. From this then E can be estimated if you assume a value for Poisson's ratio μ by

$$\ell^4 = \frac{E\,h^3}{12\,(1-\mu_p^2)\gamma_w} \qquad (12)$$

If salt water ice is the material that is used in the laboratory the salinity and temperature should always be measured. These measured values can be very useful in explaining any differences that may occur for supposedly similar ice sheets.

In all tests, laboratory or full scale, careful measurements should be made of the ice thickness.

Additional information regarding ice properties may be obtained from the reports listed under Selected References, or from those listed in the bibliography (see p. 2).

2.4 Ice Conditions

Ice conditions vary tremendously depending on location, water depth, brine content, etc. The Great Lakes, for example, vary from almost arctic conditions to open water. The southern lake areas have always had year-round navigation with few problems. The major ice problem in the Great Lakes and St. Lawrence Seaway system is in the rivers and connecting channels. These areas can experience huge ice buildups similar to ice jams or an accumulation of frazil ice which can stop all movement. Frazil ice forms in open turbulent areas and then deposits in the slower reaches. Frazil accumulations have been reported to a depth of 80 ft.

The Arctic Ocean provides the greatest difficulty for vessel movement. There are presently no commercial vessels that have the capability to transit the Arctic Ocean area during the winter. The ice thickness will be greater than 2 m with many large pressure ridges present. The central basin will consist of mostly multiyear ice (greater than 3.0 m) held together by the presence of ice in the coastal and offshore provinces.

During the summer there can be vast amounts of open water in both the coastal and offshore provinces. By the use of helicopters for route inspection it may be possible to navigate in this area. The common practice is for the helicopters to direct the vessels to the areas of little or no ice. This method was used to assist the USS Manhattan through the Northwest Passage.

The Baltic Sea, including the Gulfs of Bothnia and Finland, remains a major transportation route year-round. The countries within this area have combined efforts to keep vessels moving during the ice season. The ice thickness in the northern part of this area can be greater than 1 meter. This area is also characterized by the presence of many ice ridges, some of which are frozen to the bottom. Traffic is kept moving with the aid of a large fleet of icebreakers.

Additional information may be obtained from the reports listed under Selected References, or from those listed in the bibliography (see p. 2).

ACKNOWLEDGMENTS

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SELECTED REFERENCES

Crago, W.A., Dix, P.J. and German, C.J. "Model Icebreaking Experiments and their Correlation with Full Scale Data." RINA Transactions, Vol. 112, 1970.

Dykins, J.E. "Ice Engineering: Material Properties of Saline Ice for a Limited Range of Conditions." Naval Civil Engr. Lab. Tech. Rep. R720, 95 pp., Port Hueneme, Calif., 1971.

Edwards, R.Y. and Lewis, J.W. "Modeling the Motions of Ships through Polar Ice Fields Using Unconstrained Self Propelled Models." Reykjavik Ice Symposium, 1970.

Edwards, R.Y. et al. "Full Scale and Model Tests of a Great Lakes Icebreaker." SNAME Transactions, November 1972.

Enkvist, E. "On the Resistance Encountered by Ships Operating in the Continuous Mode of Icebreaking." Report No. 24, Swedish Academy of Engineering Sciences in Finland, 1972.

Frankenstein, G.E., Editor. "Proceedings, Third International Symposium on Ice Problems. IAHR publication, August 1975.

German, J.G. et al. "Full Scale Testing in Ice of Three Icebreakers." SNAME Ice Tech. Symposium Report, pp. H1-H37, April 1975.

Great Lakes - St. Lawrence Seaway Navigation Season Extension Demonstration Program, 1st Annual Report.

Hibler, W.D., III. "Statistical Variations in Arctic Sea Ice Ridging and Deformation Rates." SNAME, Montreal, April 1975.

Johansson, B.M. and Makinen, E. "Icebreaking Model Tests: Systematic Variations of Bow Lines and Main Dimensions of Hull Forms Suitable for the Great Lakes." SNAME Marine Technology, July 1973.

Kashteljan, V.I., Poznjak, I.I. and Ryvlin, A.J. "Ice Resistance to Motion of a Ship." Sudostroenie, Leningrad, 1968. (U.S. Translation)

Keinonen, A. "Presentation of Sea Ice Ridges in General and Physical Characteristics of Baltic Ridges for Ship Resistance Calculations." Research Report #24, Winter Navigation Research Board, Helsinki, Finland, 1978.

LeCourt, E.J., McIntosh, J.A. and Welsh, J.P. "Final Test Plan for USCGC Polar Star Ice Trials." USCG Report TR 165-C, December 1975.

Levine, G.H., Benze, D.L. and Peter, J.J. "Design, Construction and Operation of an Ice Model Basin." Chesapeake Section of Society of Naval Architects and Marine Engineers paper, November 1972.

Lewis, J.W. "Ship Model Ice Resistance Experiments." U.S. Coast Guard R&D report for project 731343, December 1972.

Lewis, J.W. and Benze, D.L. "Technical Progress Report of Model Ice Resistance Tests of the USCGC Mackinaw." Arctec Report 00771-3, 1971.

Makinen, E. "The Importance of Full Scale Testing in Ice for Designing Icebreaking Ships." Schiff Bautechnischen Gesellshaft Report, 1976.

Makinen, E. "Ship Model Testing in Ice: Possibilities and Reliability." POAC Report at Reykjavik Ice Symposium, 1970.

Makinen, E. and Keinonen, A. "Ice Resistance Measurements on Ridges." POAC Report at University of Alaska, 1975.

Milano, V.R. "Ship Resistance to Continuous Motion in Ice." Ph.D. Dissertation, Stevens Institute of Technology, 1972.

Mookhock, A.D. and Bielstein, W.J. "Problems Associated with the Design of an Arctic Marine Transportation System." Offshore Technology Preprint Paper 1426, 1971.

Nogid, L.M. "The Resistance to Forward Motion of an Icebreaker in Pack Ice Based on Model Data." Transaction of the Leningrad Shipbuilding Institute, 1959.

Palosuo, E. "A Description of Ice Period in the Baltic." ITTC Ice Panel Report, 1978.

Peyton, H.R. "Sea Ice Strength." University of Alaska Report U.A.G.-R182, December 1966.

Sayward, J.M. "Modeling Ice Study." CRREL Technical Note, April 1972.

Schwarz, J. "On the Flexural Strength and Elasticity of Saline Ice." Proceedings of 3rd International Symposium on Ice Problems, G. Frankenstein, editor, Hanover, New Hampshire, 1975.

Schwarz, J. "New Development in Modeling Ice Problems." POAC 77 Conference, Memorial University of Newfoundland. September 1977.

Schwarz, J. "Arktische MeBlahrt mit M.S. Werderfor." HSVA-Report, May 1978.

Vance, G.P. "A Modeling System for Vessels in Ice." University of Rhode Island, Ph.D. Thesis, 1974.

Voelker, R.D. et al. "Comparative Evaluation of Model I/B Test of Windclass Icebreakers." Arctec Report, 1971.

Wass, V.H. et al. "The New Ice Tank of the Hamburg Ship Model Basin." Hamburg Ship Model Basin Report, August 1972.

Weeks, W.F. "Sea Ice Properties and Geometry. AIDJEX, 1976.

Weeks, W.F. and Assur, A "Mechanical Properties of Sea Ice." CRREL Monography II-C3, 1967.

Zubov, N.N. "Arctic Ice." U.S. Naval Electronic Laboratory, May 1943.

3. DRAFT RECOMMENDATIONS OF THE 15th ITTC

The following recommendations are divided into three categories: general recommendations pertaining to the subject matter, specific recommendations for the next ITTC ice panel or committee, and recommendations directed to ship owners, operators and builders.

3.1 General Recommendations

The 15th ITTC Conference recommends:

1. That the specific procedures and techniques recommended in this report be adopted for international use.

2. That model and full scale testing in ice (including ice properties and ice conditions) should be continued and every opportunity be taken to make careful correlation analysis between the model and full scale results.

3. That continued investigations be made into the testing of models and ships in all ice conditions with the view of eventual adoption of standard techniques.

4. That the development of model ice be continued in order to better satisfy the laws of similitude.

3.2 Recommendation Directed to the Ice Panel

The 15th ITTC Conference recommends:

1. That the development of analytical prediction methods for the performance of vessels and structures in ice be continued and that the ice panel review and rereport on these methods at the next ITTC.

2. That the ice panel consider planning the testing of a model standard series for ice-transiting vessels.

3.3 Recommendations Directed to Ship Owners, Operators and Builders

The 15th ITTC Conference recommends:

1. That ship owners and/or builders allow for model and full scale testing of all vessels that have been designed for ice-transiting.

2. That ship owners and/or operators of ice-transiting vessels be encouraged to collect reliable ice voyage data during operational voyages.